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# NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

## TECHNICAL NOTE 1937

# A FLIGHT INVESTIGATION OF THE EFFECTS OF COMPRESSIBILITY ON APPLIED GUST LOADS

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## SUMMARY

Two jet-propelled airplanes were flown at different speeds in rough air to investigate the effects of compressibility on applied gust loads. Data were obtained over a Mach number range of 0.25 to 0.68 for effective gust velocities up to 15 feet per second. An analysis of the results indicated that no compressibility correction to the slope of the lift curve was necessary up to a Mach number of 0.68 for gust velocities up to 9 feet per second. Data obtained for gust velocities greater than about 9 feet per second were insufficient for analysis.

## INTRODUCTION

Only a limited amount of data is available on the effect of compressibility on the aerodynamic characteristics of an airplane in rough air. In the absence of such data, compressibility has been neglected in gust-load calculations in some cases and in other cases the effects have been approximated, as for steady-flight loads, by applying the Glauert-Prandtl factor to the slope of the lift curve.

In order to obtain information on the effects of compressibility on applied gust loads, a cooperative flight investigation was undertaken by the National Advisory Committee for Aeronautics and the All Weather Flying Division of the U. S. Air Force at Clinton County Air Force Base, Wilmington, Ohio. This investigation is believed to be the first attempt to obtain aerodynamic information by the statistical comparison of airplane reactions. Test data over a Mach number range of 0.25 to 0.68, corresponding to speeds from 200 to 500 miles per hour, have been obtained from flights of two jet-propelled airplanes in rough air in the vicinity of Wilmington, Ohio. The results of the investigation to determine the validity of steady-flow compressibility corrections to the slope of the lift curve in gust-load calculations are presented herein.

## APPARATUS

A three-view drawing of the airplanes used in the investigation is shown in figure 1. The characteristics of the airplanes as flown are given in table I. Wing tip tanks were installed for flights up to a Mach number of 0.62 and were removed for flights up to a Mach number of 0.68. No attempt was made to improve air-flow characteristics by smoothing the wings or fuselage.

The instruments installed in each airplane to determine the effective gust velocities encountered in the flights were as follows:

(1) NACA air-damped accelerometer

(2) NACA airspeed-altitude recorder

(3) NACA timer (1-second interval)

The accelerometer was located in the pilot's compartment approximately $5\frac{1}{2}$ feet forward of the center of gravity of the airplane. The airspeed-altitude recorder, timer, and power supply were installed in the nose section of the airplane in the location normally occupied by the armament.

The NACA air-damped accelerometer had a natural frequency of about 20 cycles per second. The total-pressure lead from the NACA airspeed-altitude recorder was connected to an airspeed head mounted below the nose of the airplane. The static-pressure leads from the recording instruments were connected to the static-pressure vents located on the forward part of the fuselage. The instruments were supplied with drums which held 50 feet of film and were operated at a film speed of 1/4 inch per second. Time synchronization between the airspeed and accelerometer records was effected by means of the 1-second timer.

## METHOD AND TESTS

The procedure used in obtaining flight data consisted of flying an airplane through clear rough air over a given course at one altitude but at different speeds. For the clear-air conditions encountered, the distribution of the gusts over the course was assumed to remain constant over the short period of time covered by each flight. The variations in the apparent gust-frequency distribution as computed from the reactions of the airplane should be primarily due to the difference in Mach number.

The tests consisted of 21 flights over a course of about 55 miles and were made in the vicinity of Clinton County Air Force Base, Wilmington, Ohio. All flights were made through clear rough air at an altitude of about 2500 feet. Each flight consisted of successive runs over the course at speeds of 200, 350, and 450 miles per hour. A single airplane was used in 14 of the flights (six flights with wing tip tanks installed and eight flights with wing tip tanks removed); whereas two airplanes were used in the seven remaining flights.

In the flights with a single airplane with wing tip tanks installed, the pilot made a run over the course at a speed of 200 miles per hour, returned at 350 miles per hour, and again retraced the course at 450 miles per hour. The instruments were started and stopped directly over the end points of the course on each run. The average time elapsed between the start of the run at 200 miles per hour and the end of the run at 450 miles per hour was 35 minutes. A total of 325 miles was flown at each speed. Three flights were flown by one pilot and the other three flights were flown by another pilot.

In the flights with two airplanes, the first pilot made a run at 200 miles per hour and returned at 450 miles per hour while the second pilot made the initial run at 450 miles per hour and returned at 200 miles per hour. The start of each run was so timed that the airplane traveling at high speed would overtake the airplane traveling at low speed about the midpoint of the course. A total of about 650 air miles for each airplane was flown in this manner.

In the flights with a single airplane with wing tip tanks removed, the pilot made a run over the course at a speed of 200 miles per hour and retraced the course at 500 miles per hour. A total of about 370 air miles was flown in this manner. Six flights were flown by one pilot and the other two flights were flown by another pilot.

The data obtained from one of the single-airplane flights have not been included in the present analysis because the airplane was not flown in accordance with the procedures set up for this investigation. In addition, data obtained from two of the two-airplane flights were not used because in one case the airplanes were not flown over the proper course and in the other case the airplanes encountered storm clouds.

The procedures used in this investigation attempted to eliminate or average out the effects of as many of the extraneous variables as possible. The pilot assignments and the order of the high-speed and low-speed runs were varied in a random manner to eliminate any consistent combination of conditions that might affect the results. Furthermore, the results are presented in terms of the average miles to exceed a given gust velocity in order that the effects of any reading inaccuracies, instrument inaccuracies, and minor variations in flight-path length may be eliminated.

In order to obtain data on the effects caused by different pilots and airplanes on gust loads, the airplanes were flown side by side as extra runs over the course on five of the flights in which two airplanes were used. A total of 250 air miles for each airplane was flown in this manner.

In addition to the test flights described, flights were made to calibrate the airspeed installations of the airplanes.

## RESULTS

The acceleration records were evaluated to obtain the magnitude of all acceleration increments from the 1 g datum. The evaluation was confined to single maximums and minimums, or peaks, between any two consecutive intersections of the record line with the 1 g reference level. Two procedures were used in evaluating the airspeed-altitude records. The records obtained from about one-third of the flights had the airspeed read for each acceleration peak; whereas, in the remaining records, an average airspeed was used for parts of the record for which the airspeed remained fairly constant.

The data read from the records were used to obtain the effective gust velocities, reference 1. The evaluation was made for three conditions:

(1) When all compressibility corrections were disregarded, the formula used was

$$U_e = \frac{2 \Delta n W}{\rho_o S K V_e a} \tag{1}$$

(2) When the compressibility correction for finite aspect ratio was assumed to apply, the effective gust velocity was computed from the formula

$$U_e = \frac{2 \Delta n W}{\rho_o S K V_e a_c} \tag{2}$$

where

$$a_c = a\left[\frac{\sqrt{A^2 + 4} + 2}{\sqrt{A^2(1 - M^2) + 4} + 2}\right]$$

This correction factor is obtained by correcting the work of reference 2 for compressibility by the Glauert-Prandtl factor.

(3) When the Glauert-Prandtl compressibility correction for infinite aspect ratio was assumed to apply, the effective gust velocity was computed from the formula

$$U_e = \frac{2\ \Delta n\ W}{\rho_o S K V_e a \dfrac{1}{\sqrt{1 - M^2}}} \tag{3}$$

where

$U_e$ effective gust velocity, feet per second (reference 1)

$\Delta n$ acceleration increment, g units

$W$ weight of airplane at time acceleration was experienced, pounds

$\rho_o$ air density at sea level, slugs per cubic foot

$S$ wing area, square feet

$K$ relative alleviation factor (reference 1)

$V_e$ equivalent airspeed, feet per second (reference 3)

$a$ slope of the lift curve, per radian

$A$ aspect ratio

$M$ Mach number

The same value for the slope of the lift curve has been used for the airplane with wing tip tanks installed or removed. The effect of tip tanks on the slope of the lift curve does not alter the validity of the conclusion to be drawn in this paper.

The frequency distributions of effective gust velocities obtained from equations (1) to (3) for each speed for the single-airplane flights are shown in table II. The air miles flown at each speed are also included in table II. The frequency distributions and air miles flown for the two-airplane flights are shown in table III. The frequency distributions and air miles flown for the flights of a single airplane with tip tanks removed are shown in table IV.

The distributions and the air mileages in tables II to IV were used to obtain the average number of flight miles to exceed a given gust velocity at each speed. The results obtained from the single-airplane flights for the three assumed conditions are shown in figure 2. Figure 3

shows similar results for the two-airplane flights. Figure 4 shows the results obtained from the flights of a single airplane with wing tip tanks removed.

## PRECISION

Inaccuracies in the acceleration data due to instrument and reading errors are estimated to be less than ±0.05g. This estimate is based on dynamic calibrations of the accelerometers and on check readings of the records by different personnel.

The airspeed calibration is estimated to be accurate within 0.5 percent. The use of an average airspeed for short lengths of the records of some of the flights introduced an additional probable error of about 2 percent in the calculations for equivalent airspeed.

On the basis of the errors in airspeed and acceleration, the maximum error in a given value of effective gust velocity is 1.0 foot per second. Since the error is random, the probable error in the combined data of figures 1 to 3 is estimated to be about 0.2 foot per second at 200 miles per hour and 0.1 foot per second at 450 miles per hour.

## DISCUSSION

Consideration of figure 2(a) indicates that for gust velocities up to 9 feet per second the apparent gust experience of the airplane is in excellent agreement for the test Mach numbers of 0.28, 0.48, and 0.62 when compressibility is neglected. Figure 2(b) shows an orderly displacement with speed when the finite-aspect-ratio correction is used. Figure 2(c) also shows an orderly displacement with speed when the infinite-aspect-ratio correction is used, but the variation between the curves is greater than in figure 2(b). The increased spread in the curves of figures 2(b) and 2(c) and the somewhat random variation in the curves of figure 2(a) at gust velocities above 8 or 9 feet per second are not considered significant because of the small amount of data at the higher gust velocities. Inasmuch as the single-airplane flights involve only one pilot for each flight, it appears that the pilot would not be a factor. The differences in the apparent gust experience shown in figures 2(b) and 2(c) are therefore due to differences in Mach number. On the basis that the actual gust experience at each speed is the same, figure 2(a) indicates that the effect of compressibility on the slope of the lift curve for the purpose of calculating gust loads is negligible for the test airplane in rough air. Since wind-tunnel tests indicate a

compressibility correction to the lift-curve slope of this airplane, steady-flow tests do not appear to be adequate for gust-load calculations. These results warrant further investigation before they are applied to other aircraft.

The interpretation of the results of the two-airplane flights is less obvious. Although the results agree qualitatively with those of the single-airplane flights in that the apparent gust experience for high speed is shifted in the same direction when the compressibility corrections are applied (figs. 3(b) and 3(c)), neither correction gives an exact agreement between the curves. If the findings are accepted at face value, some effect of compressibility would be indicated. (See fig. 3(a).) A careful study of the data for the individual flights with two airplanes suggests that the disagreement between results for the single- and two-airplane flights may be due to the introduction of the second pilot and airplane. The factor influencing the data appears to be the distraction of the pilots in coordinating their runs. Furthermore, the data are limited to two speeds as compared with three speeds in the single-airplane flights. On the basis of this study, the results from the two-airplane flights are not believed to be as reliable as the results from the single-airplane flights for evaluating the small effects concerned herein.

The results for a Mach number range of 0.28 to 0.68 from the flights with wing tip tanks removed (fig. 4) are the same as the results given in figure 2 in spite of the changed configuration that affects the stability and elastic response of the structure. The results shown in figure 2 are therefore substantiated, and it is concluded that no compressibility correction to the slope of the lift curve was necessary for gust-load calculations on the test airplanes up to a Mach number of 0.68 and for gust velocities up to 9 feet per second.

The slope of the lift curve is the parameter in gust-load calculations that is most obviously susceptible to compressibility effects but there may be a question as to whether the results obtained herein are real or are caused by less obvious factors that compensate for an actual increase in the slope of the lift curve with speed. For example, if the effect of boundary layer on the slope of the lift curve is assumed to be a function of the rate of change of angle of attack, the effect of boundary layer would not be a factor because the rate of change of angle of attack due to a gust of fixed size and intensity is independent of forward speed. The information available on the change of unsteady-lift functions with Mach number indicates that the effect on gust loads would be of the wrong sign to compensate for an increase slope of the lift curve. The adequacy of acceleration measurements at the center of gravity for computing gust loads on modern airplanes might be in question inasmuch as aeroelastic effects may have a significant effect on the accelerations measured at the center of gravity. The flights with wing tip tanks removed (fig. 4(a)) represent a different elastic characteristic of the

wing from that for the flights with wing tip tanks installed (fig. 2(a)). Inasmuch as the data show excellent agreement, it would appear that the effect of aeroelasticity may be neglected for the purpose of this investigation. Changes in stability with speed for the test airplane have been shown by flight tests at the Ames Laboratory to be negligible over the Mach number range used herein.

## CONCLUDING REMARKS

A flight investigation with two jet-propelled airplanes for determining the effects of compressibility on applied gust loads has shown that the effects in rough air were negligible within the test range. These results indicated that no compressibility correction to the slope of the lift curve was necessary for the test airplane up to a Mach number of 0.68 and for gust velocities below 9 feet per second. Data obtained for gust velocities greater than 9 feet per second were insufficient for analysis.

Similar tests on a different airplane type and at higher Mach numbers are desirable before any general conclusions are drawn.

Langley Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Air Force Base, Va., March 28, 1949

## REFERENCES

1. Rhode, Richard V., and Donely, Philip: Frequency of Occurrence of Atmospheric Gusts and of Related Loads on Airplane Structures. NACA ARR L4I21, 1944.

2. Polhamus, Edward C.: A Simple Method of Estimating the Subsonic Lift and Damping in Roll of Sweptback Wings. NACA TN 1862, 1949.

3. Aiken, William S., Jr.: Standard Nomenclature for Airspeeds with Tables and Charts for Use in Calculation of Airspeed. NACA Rep. 837, 1946.

TABLE I

AIRPLANE CHARACTERISTICS

| | Airplane A | Airplane B |
|---|---|---|
| Gross weight at take-off, pounds | 14,268 | 14,362 |
| Center-of-gravity location, percent M.A.C. | 28.6 | 29.8 |
| Span, feet | 38.8 | 38.8 |
| Mean aerodynamic chord, feet | 6.7 | 6.7 |
| Wing area, (including projected fuselage area), square feet | 237 | 237 |
| Wing loading at take-off, pounds per square foot | 60.2 | 60.6 |
| Slope of the lift curve for incompressible flow, per radian | 4.7 | 4.7 |
| Wing fundamental bending frequency, tip tanks full, cycles per second | 2.4 | 2.4 |
| Wing fundamental bending frequency, tip tanks empty, cycles per second | 5.8 | 5.8 |

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TABLE II

FREQUENCY DISTRIBUTION OF EFFECTIVE GUST VELOCITY BY FLIGHT SPEED

FOR THE SINGLE-AIRPLANE FLIGHTS WITH TIP TANKS

| $U_e$ (fps) | Frequency distribution without compressibility correction | | | Frequency distribution with finite-aspect-ratio correction | | | Frequency distribution with Glauert-Prandtl correction | | |
|---|---|---|---|---|---|---|---|---|---|
| | Flight speed, miles per hour | | | | | | | | |
| | 200 | 350 | 450 | 200 | 350 | 450 | 200 | 350 | 450 |
| 4 to 5 | 211 | 315 | 326 | 229 | 362 | 218 | 235 | 385 | 235 |
| 5 to 6 | 194 | 251 | 210 | 176 | 166 | 130 | 166 | 150 | 94 |
| 6 to 7 | 102 | 108 | 83 | 111 | 100 | 71 | 116 | 74 | 50 |
| 7 to 8 | 70 | 68 | 56 | 65 | 42 | 32 | 55 | 46 | 30 |
| 8 to 9 | 34 | 31 | 39 | 30 | 23 | 17 | 27 | 12 | 7 |
| 9 to 10 | 18 | 16 | 21 | 20 | 10 | 4 | 14 | 10 | 2 |
| 10 to 11 | 7 | 9 | 6 | 5 | 9 | 3 | 5 | 10 | 1 |
| 11 to 12 | 7 | 9 | 1 | 8 | 4 | 1 | 8 | 1 | 1 |
| 12 to 13 | 3 | 4 | 3 | 2 | 0 | --- | 1 | 0 | --- |
| 13 to 14 | 0 | 0 | --- | 0 | 1 | --- | 0 | 2 | --- |
| 14 to 15 | 1 | 1 | --- | 1 | 1 | --- | 1 | --- | --- |
| 15 to 16 | --- | 1 | --- | --- | --- | --- | --- | --- | --- |
| Air miles flown: | 279.4 | 268.7 | 251.8 | 279.4 | 268.7 | 251.8 | 279.4 | 268.7 | 251.8 |

TABLE III

FREQUENCY DISTRIBUTION OF EFFECTIVE GUST VELOCITY BY FLIGHT

SPEED FOR THE TWO-AIRPLANE FLIGHTS

| $U_e$ (fps) | Frequency distribution without compressibility correction | | Frequency distribution with finite-aspect-ratio correction | | Frequency distribution with Glauert-Prandtl correction | |
|---|---|---|---|---|---|---|
| | Flight speed, miles per hour | | | | | |
| | 200 | 450 | 200 | 450 | 200 | 450 |
| 4 to 5 | 568 | 589 | 611 | 509 | 577 | 630 |
| 5 to 6 | 488 | 527 | 430 | 493 | 448 | 354 |
| 6 to 7 | 283 | 353 | 299 | 233 | 284 | 174 |
| 7 to 8 | 151 | 198 | 145 | 99 | 115 | 65 |
| 8 to 9 | 68 | 107 | 73 | 41 | 72 | 42 |
| 9 to 10 | 54 | 47 | 40 | 34 | 31 | 15 |
| 10 to 11 | 9 | 28 | 10 | 13 | 11 | 14 |
| 11 to 12 | 8 | 20 | 5 | 9 | 5 | 6 |
| 12 to 13 | 3 | 11 | 4 | 4 | 1 | 1 |
| 13 to 14 | 0 | 7 | 0 | 0 | 0 | 0 |
| 14 to 15 | 1 | 4 | 1 | 1 | 1 | 1 |
| 15 to 16 | 0 | 0 | 0 | 1 | 0 | 1 |
| 16 to 17 | 0 | 1 | 0 | 1 | 0 | --- |
| 17 to 18 | 0 | 0 | 0 | --- | 1 | --- |
| 18 to 19 | 1 | 2 | 1 | --- | --- | --- |
| Air miles flown: | 525.1 | 524.4 | 525.1 | 524.4 | 525.1 | 524.4 |

TABLE IV

FREQUENCY DISTRIBUTION OF EFFECTIVE GUST VELOCITY BY FLIGHT SPEED

FOR THE SINGLE-AIRPLANE FLIGHTS WITH TIP TANKS REMOVED

| $U_e$ (fps) | Frequency distribution without compressibility correction | | Frequency distribution with finite-aspect-ratio correction | | Frequency distribution with Glauert-Prandtl correction | |
|---|---|---|---|---|---|---|
| | Flight speed, miles per hour | | | | | |
| | 200 | 500 | 200 | 500 | 200 | 500 |
| 4 to 5 | 550 | 449 | 527 | 321 | 464 | 231 |
| 5 to 6 | 264 | 269 | 209 | 126 | 211 | 78 |
| 6 to 7 | 109 | 111 | 111 | 46 | 86 | 22 |
| 7 to 8 | 47 | 49 | 50 | 12 | 45 | 8 |
| 8 to 9 | 26 | 22 | 21 | 7 | 19 | 5 |
| 9 to 10 | 10 | 7 | 10 | 4 | 7 | 0 |
| 10 to 11 | 1 | 6 | 1 | 0 | 2 | 0 |
| 11 to 12 | 1 | 4 | 1 | 1 | 0 | 1 |
| 12 to 13 | 1 | 0 | 1 | --- | 1 | --- |
| 13 to 14 | 1 | 0 | 1 | --- | 1 | --- |
| 14 to 15 | --- | 0 | --- | --- | --- | --- |
| 15 to 16 | --- | 1 | --- | --- | --- | --- |
| Air miles flown: | 379.0 | 371.5 | 379.0 | 371.5 | 379.0 | 371.5 |

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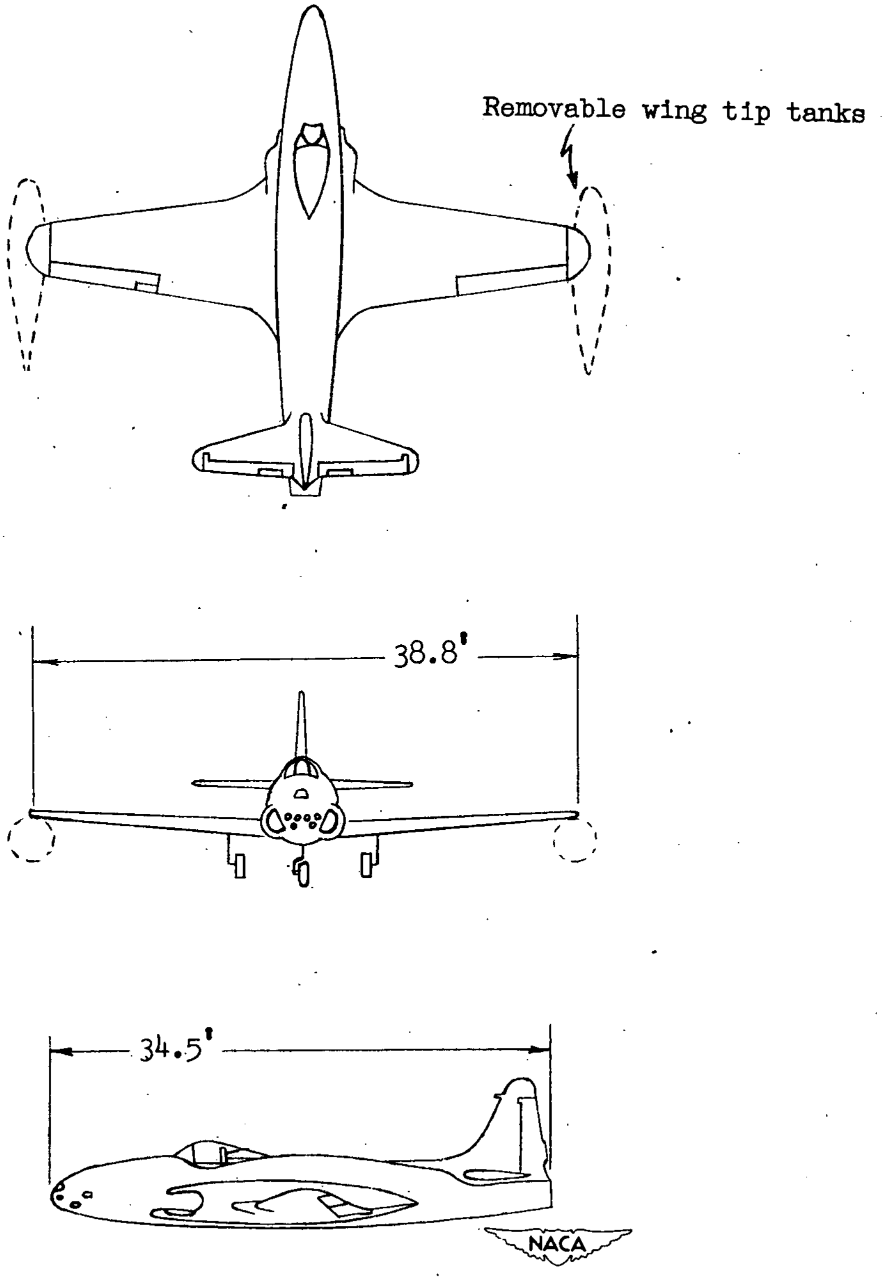
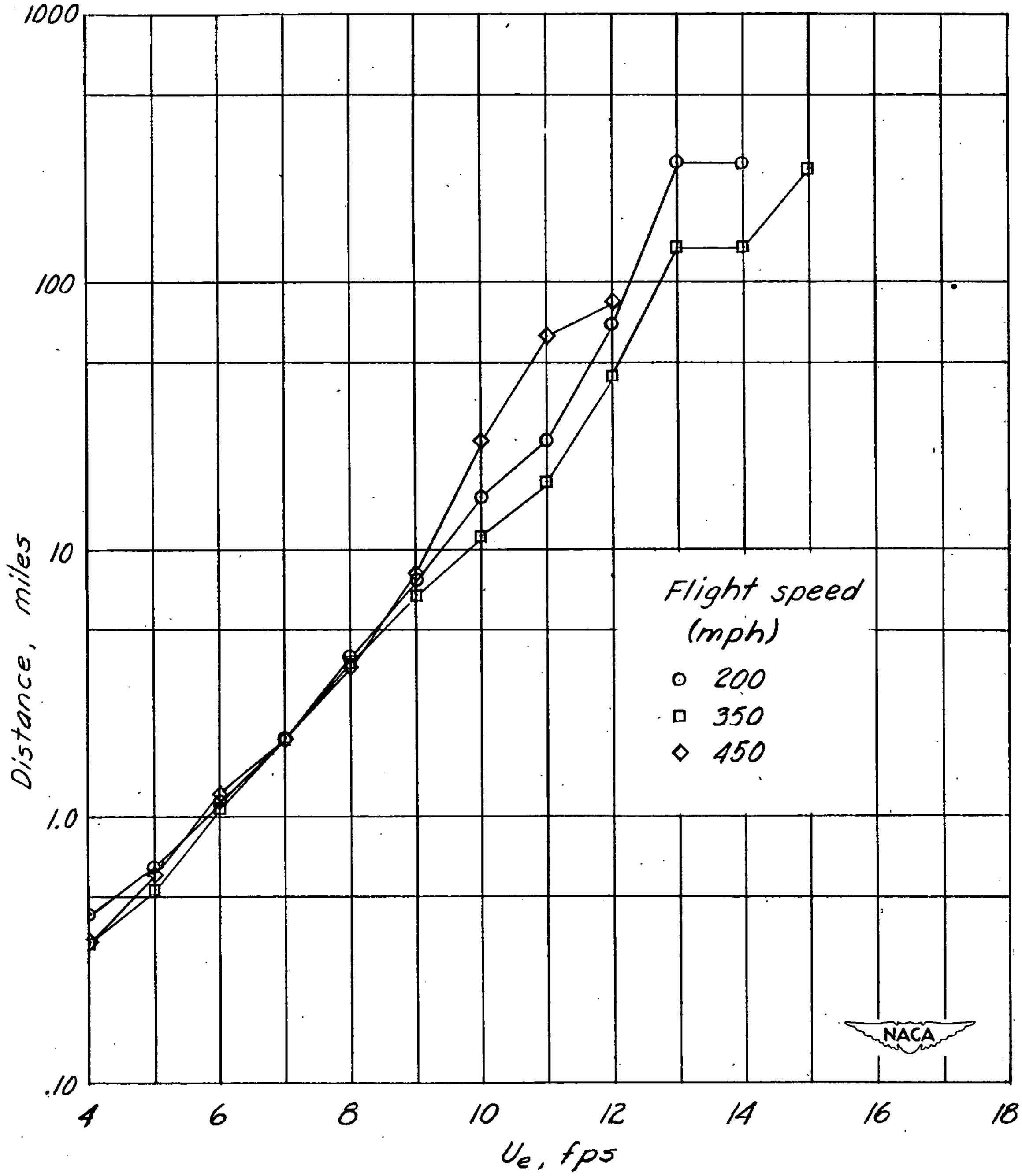
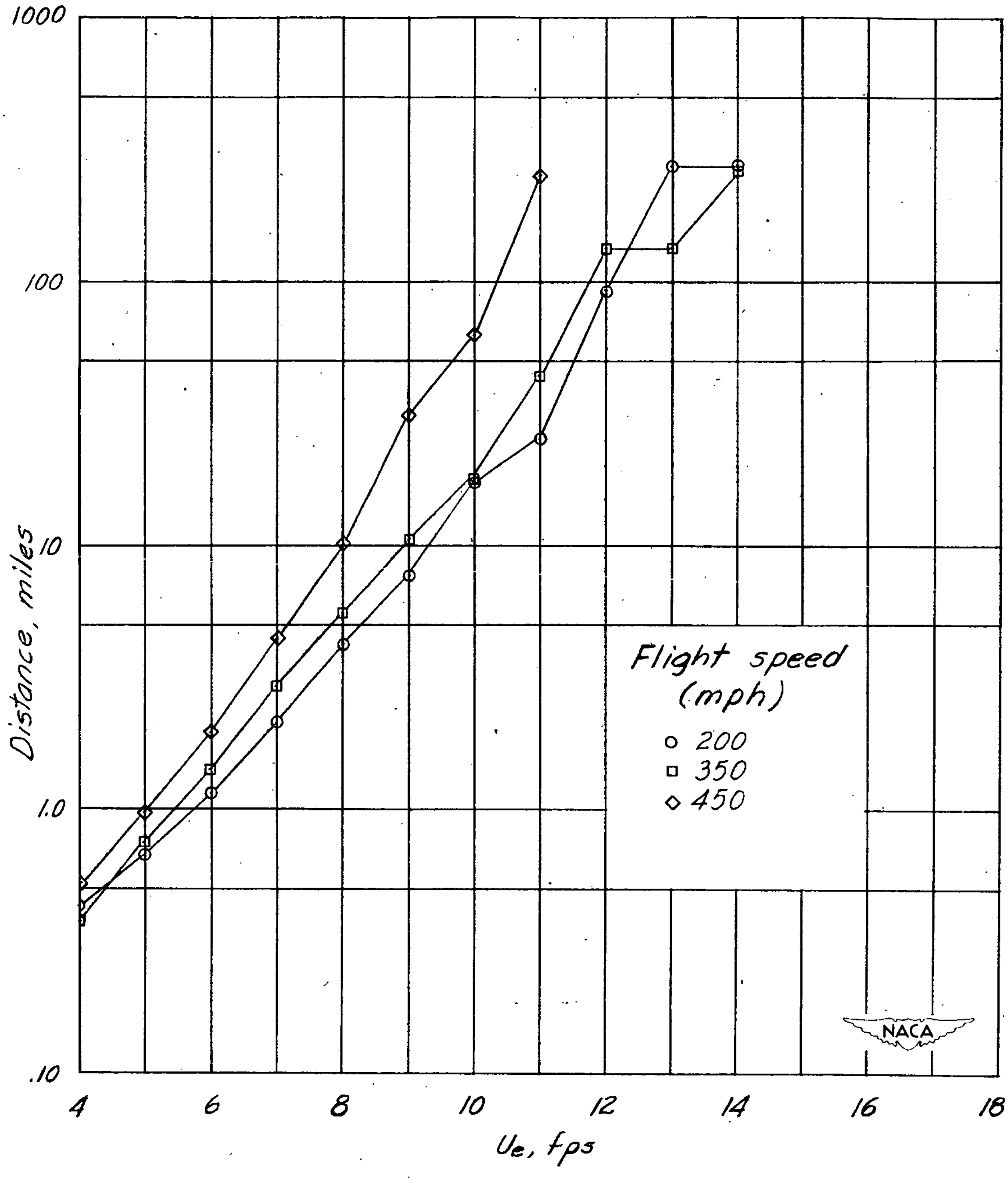



Figure 1.– Three-view drawing of test airplane.



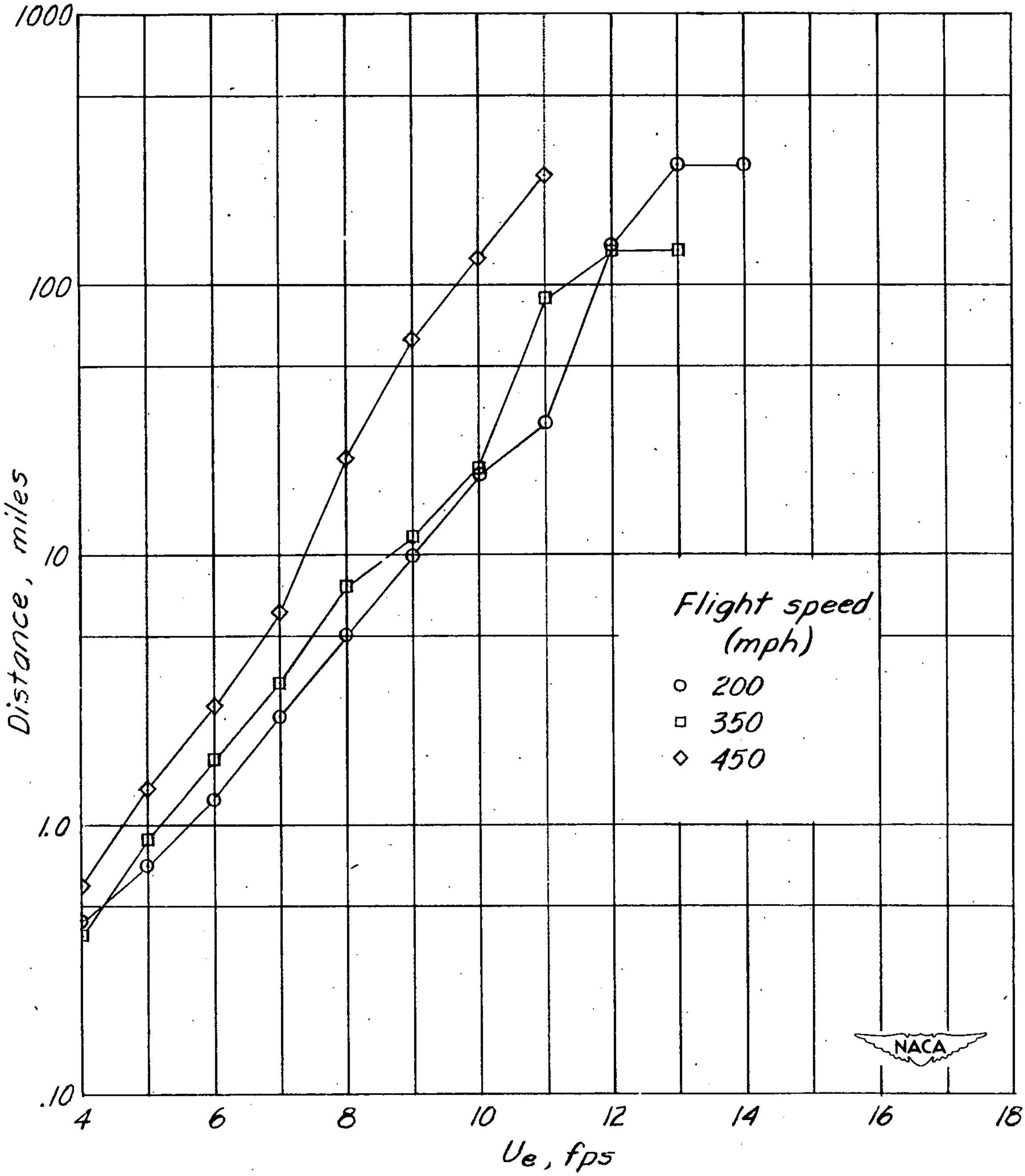

(a) Without compressibility correction.

Figure 2.- Average number of miles to exceed a given gust velocity. Single-airplane flights with tip tanks.



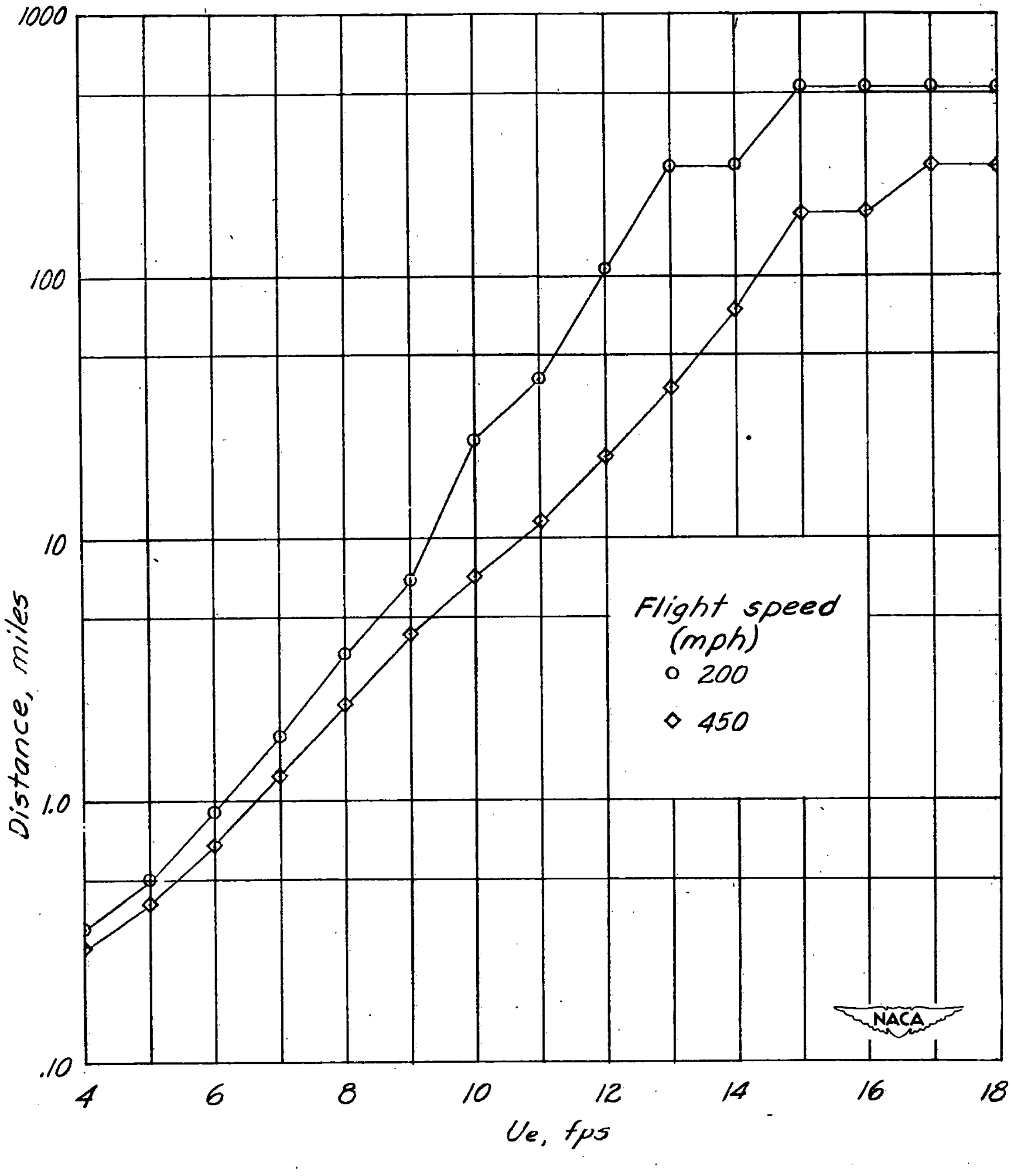

(b) With finite—aspect—ratio correction for compressibility.

Figure 2.— Continued.



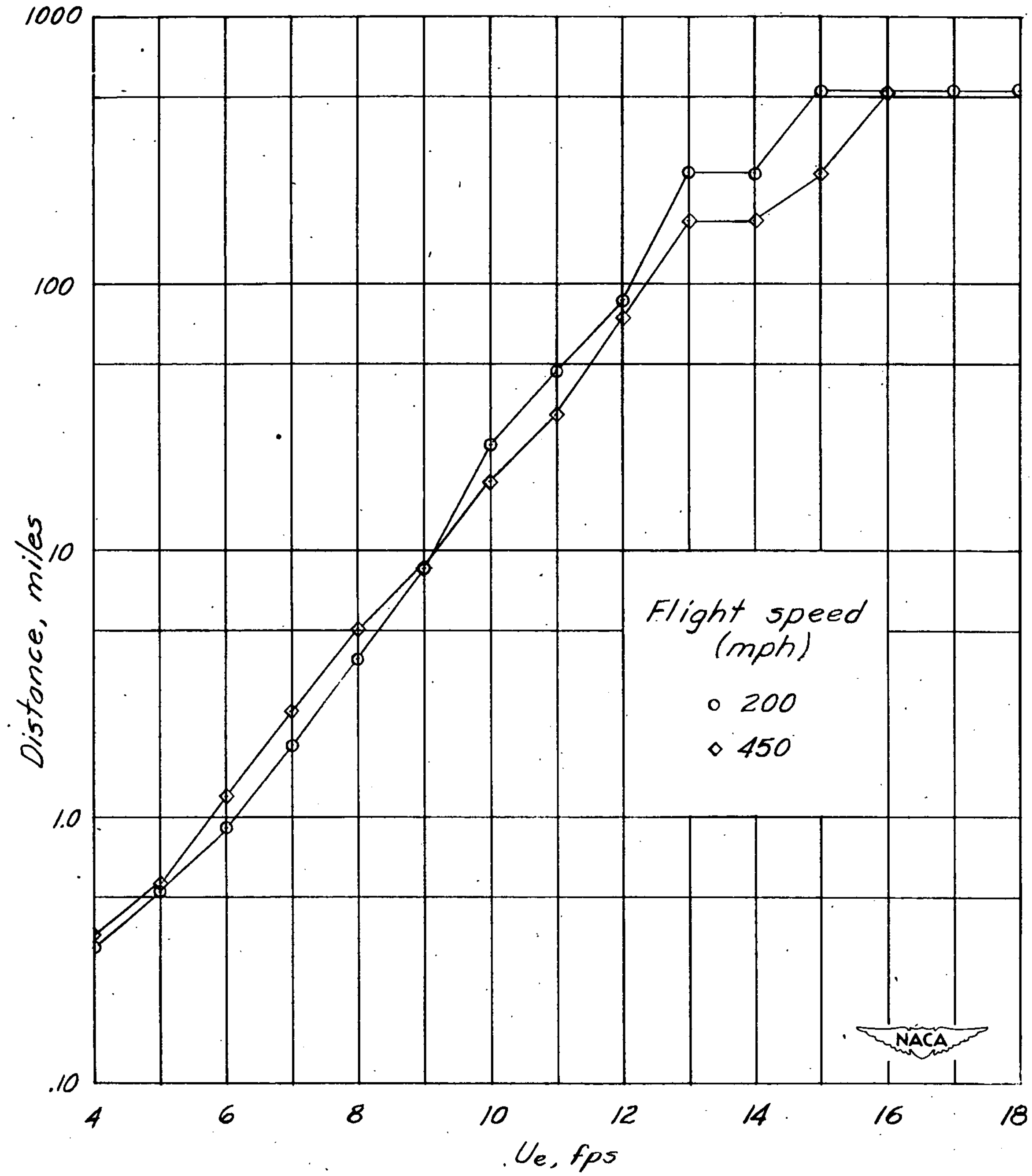

(c) With Glauert-Prandtl correction for compressibility.

Figure 2.- Concluded.



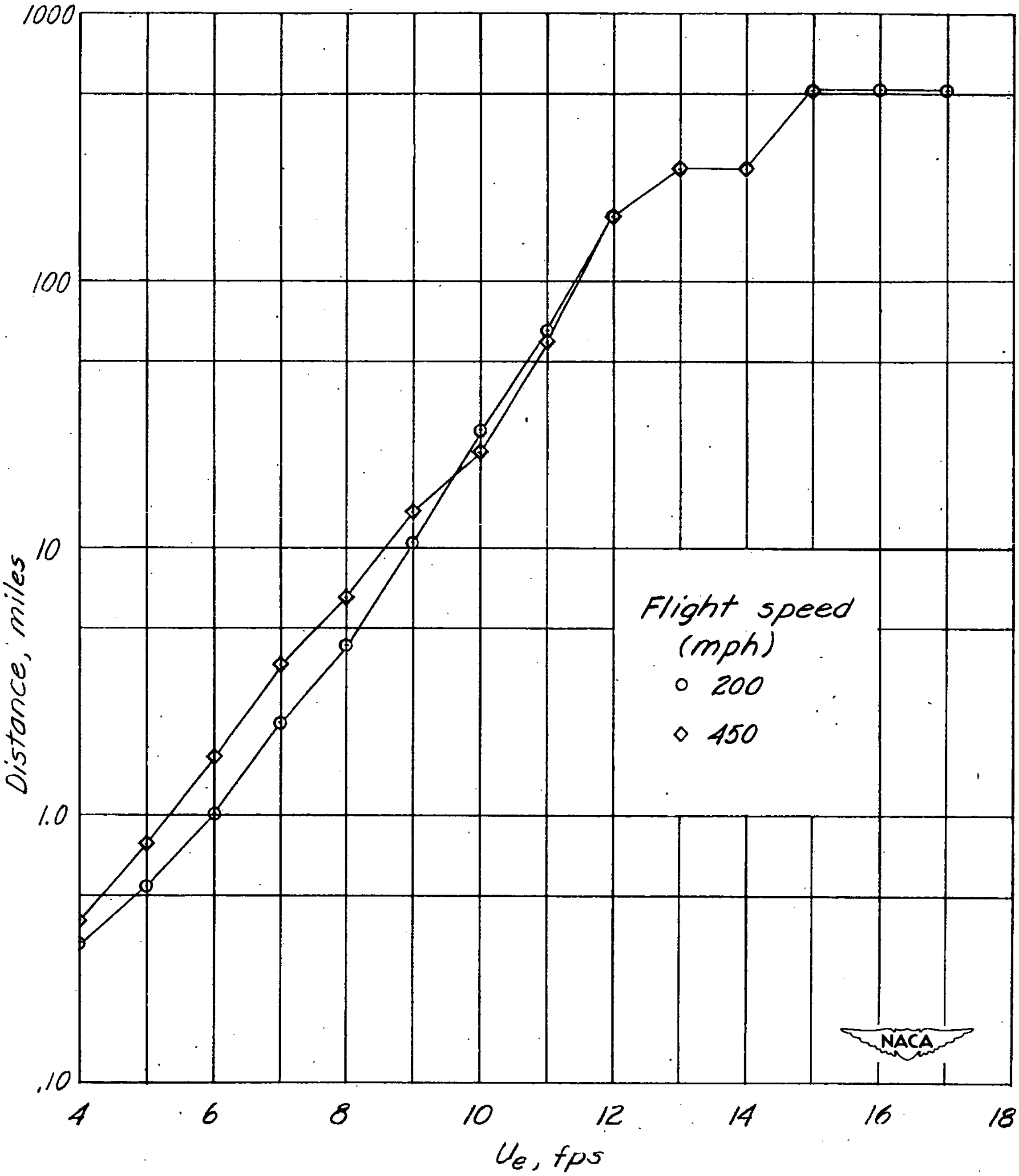

(a) Without compressibility correction.

Figure 3.— Average number of miles to exceed a given gust velocity. Two-airplane flights.



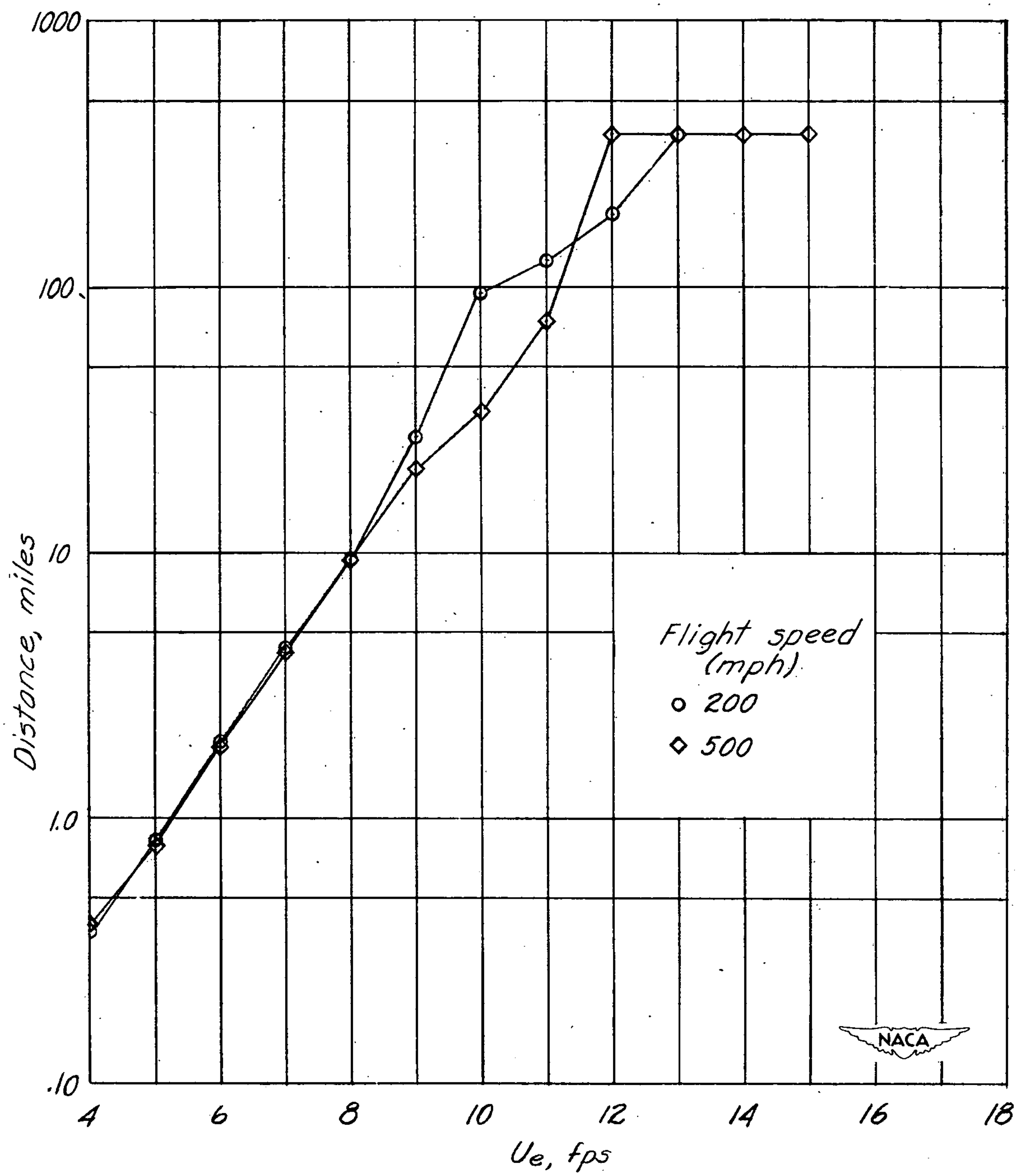

(b) With finite-aspect-ratio correction for compressibility.

Figure 3.- Continued.



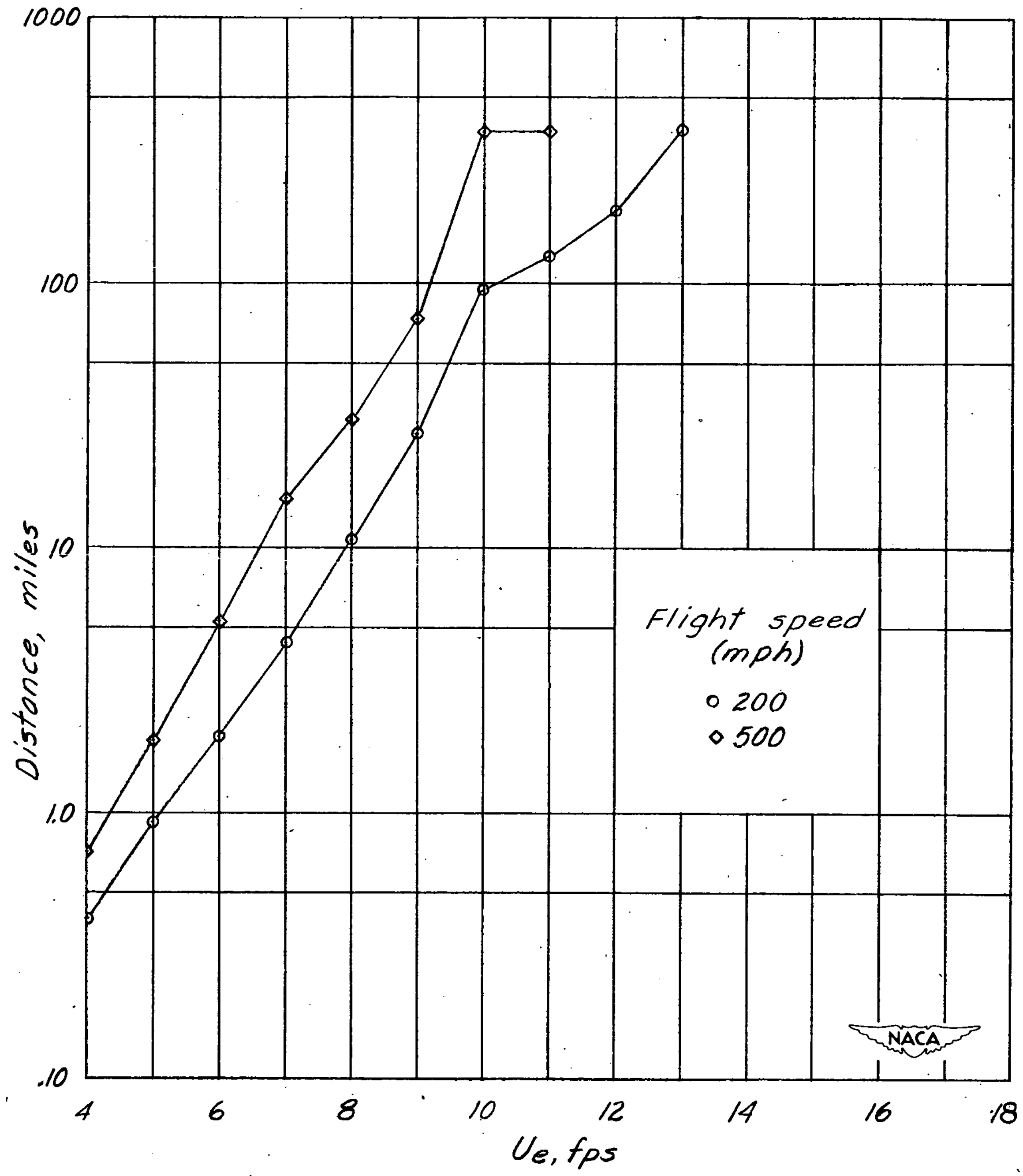

(c) With Glauert-Prandtl correction for compressibility.

Figure 3.- Concluded.



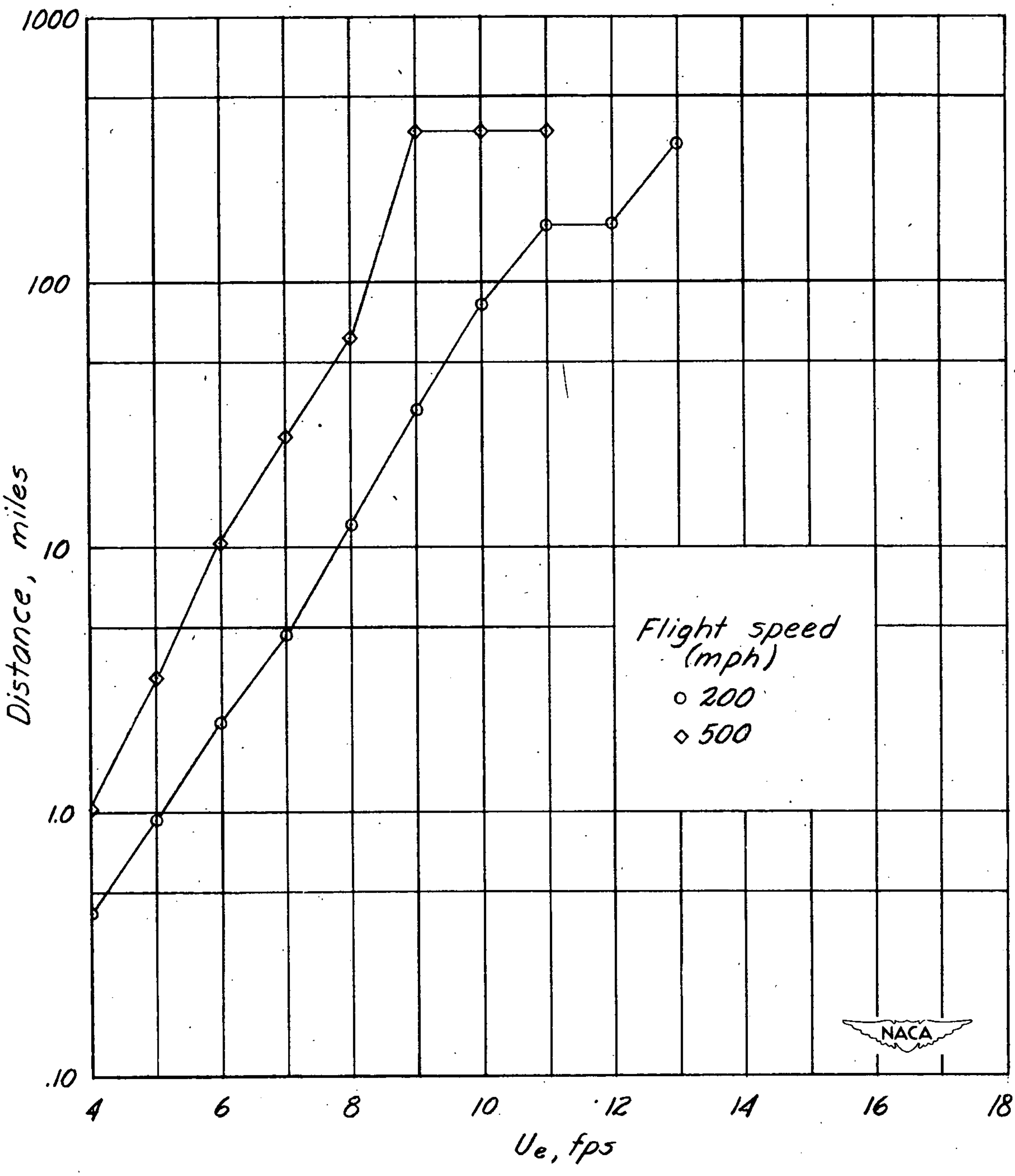

(a) Without compressibility correction.

Figure 4.- Average number of miles to exceed a given gust velocity. Single-airplane flights; wing tip tanks removed.




(b) With finite-aspect-ratio correction for compressibility.

Figure 4.– Continued.




(c) With Glauert–Prandtl correction for compressibility.

Figure 4.– Concluded.